Landscape and Urban Planning 182 (2019) 34–43

Contents lists available at ScienceDirect

Landscape and Urban Planning

journal homepage: www.elsevier.com/locate/landurbplan

Research Paper

Irrigation of green spaces and residential gardens in a Mediterranean metropolis: Gaps and opportunities for climate change adaptation

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ARTICLE INFO

Keywords:
Water-use pattern
Urban vegetation
Hydrological model
Green infrastructure
Santiago de Chile

ABSTRACT

Many cities are facing water shortages because of climate change. Climate adaptation plans have prioritized water saving to prevent the devastating consequences of drought. To develop such adaptation plans, it is critical to understand the water-use patterns of cities. The present research determines the water consumption for irrigation of green spaces and residential gardens in metropolitan area of Santiago, Chile (MAS) and compares this consumption with the expected vegetation water requirements estimated using a hydrological model. The monthly water consumption was obtained from a database of drinking water meters provided by the private water utility serving most of the MAS, which includes 110 large parks and 1882 small parks. The MAS shows higher water consumption during the summer dry months (November to April). The water use for irrigation is higher than the modelled demand of vegetation, which entails a significant chance to save water. The irrigation rate of public spaces is lower than private spaces, and closer to the modelled demand. In all cases, the landscaping based on extensive lawn surfaces seems to be the main driver of over-irrigation. Further research is required to study the trade-offs between the urban green benefits and the costs of irrigation in semi-arid and Mediterranean cities.

1. Introduction

Many cities are facing water shortages because of climate change. Population growth and urban sprawl have exacerbated this situation because a rising demand for fresh water for both human use and productive processes (e.g., industry and services) has been generated in the context of growing scarcity (Arnell et al., 2016; Hof & Wolf, 2014). Different climate projections agree that, by the end of the 21st century, the global surface temperature is likely to exceed 1.5 °C relative to pre-industrial conditions for all emission scenarios, and is likely to exceed 2 °C for the highest emission scenarios (Arnell et al., 2016; IPCC, 2013). Although some recent publications claim that these could be overly optimistic projections (Beckage et al., 2018). These warming trends will change the global water cycle over the 21st century, increasing the contrast in precipitation between wet and dry regions, and between wet and dry seasons (IPCC, 2013). Climate adaptation plans formulated to address these impacts by various national and international instances (e.g., the EU Adaptation Strategy, United Nations Framework Convention on Climate Change (UNFCCC), and sub-national plans by Araos et al. 2016) have prioritized water saving to prevent the devastating consequences of drought on human populations, ecosystems, and biodiversity. To develop such adaptation plans, it is critical to understand the water-use patterns of cities. However, there is a lack of data regarding the chances of reducing the per capita consumption when considering the differences among people, lifestyles, and income levels (Hof & Wolf, 2014). This challenge of adaptation to climate change has been mostly studied in relation to agricultural activities, although a few studies related to urban demand have been conducted (e.g. Bonelli, Vicuña, Meza, Gironás, & Barton, 2014).

Urban water use can be broken down into indoor consumption (e.g., drinks, food preparation, and washing) and outdoor consumption (e.g., irrigation and pools). Outdoor consumption is a growing concern because it can represent up to 70% of residential water use, which is expanding in demand because of urban sprawl (Hof & Wolf, 2014; Wentz & Gober, 2007). However, irrigation has important implications for quality of life and human health because many ecosystem services

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https://doi.org/10.1016/j.landurbplan.2018.10.006
Received 5 March 2018; Received in revised form 17 August 2018; Accepted 9 October 2018
Available online 22 October 2018
0169-2046/

are provided for urban vegetation. The decline of irrigation can lead to a reduction of human health, and can even hinder climate change adaptation because some ecosystem services are relevant for adaptation in urban areas (such as temperature regulation, carbon sequestration, and runoff regulation). On the other hand, the irrigation of green spaces and gardens is exposed to cuts during a water shortage because it does not directly affect human consumption (Kenney, Klein, & Clark, 2004; Survis & Root, 2012). However, a problem yet to be sufficiently studied is to what extent we can reduce the amount of irrigation of these green spaces without jeopardizing urban vegetation survival.

From 2013 to 2016 a climate change adaptation project was developed for the Maipo basin. This project, called Maipo: Plan de Adaptacion (MAPA), was co-developed by scientists and different set of stakeholders who produced the key components (objectives, tools and scenarios) of a basin wide adaptation plan. More details of the project can be found in Ocampo-Melgar, Vicuña, Gironás, Varady, and Scott (2016). As part of that larger project, herein we present the results of a research project whose objectives were (i) to determine the water consumption for irrigation of green spaces and residential gardens using observations, and (ii) to compare this consumption with the expected vegetation water requirements estimated using a hydrological model. By fulfilling these two objectives, we expect to understand the opportunities for climate change adaptation because the difference between the observed and modelled consumptions allows estimating the water saving possibilities. Published studies have used different methodologies to measure or estimate the indoor and outdoor water consumption. In this study, the monthly consumption recorded by a utility providing drinking water has been used. The study was conducted in the metropolitan area of Santiago, Chile, which is described as a case study in the next section. We then present the methods used to estimate the water consumption in both public and private (residential) green spaces. A physically based hydrological model is presented as a method to estimate the climate and soil related conditions that drive the water consumption of vegetation in Santiago. Finally, we compare the observed water demand with the physically estimated demand to discuss the implications for climate change adaptation related to the irrigation of green spaces in a growing metropolis exposed to diminishing precipitation and rising water shortages.

2. Study area

The metropolitan area of Santiago (MAS) is located at 33°27′ south latitude, 70°42′ west longitude, in the foothills of the Andean Mountains with an average elevation of 567 m, in the southwest part of South America (Fig. 1). The MAS is characterized by a Mediterranean, semi-arid climate with rainy winters, and a long dry season from November to May. The annual mean temperature is around 13.5 °C, with a maximum annual mean of 21 °C and a minimum annual mean of 6 °C. The annual average rainfall ranges from 332 to 400 mm depending on the location within the city. Owing to a lack of rainfall, irrigation of urban vegetation is a common practice during the dry season. Climate conditions are already changing (Boisier, Rondanelli, Garreaud, & Muñoz, 2016; Falvey and Garreaud, 2009) here, and are expected to change further (Meza, Vicuña, Jelinek, Bustos, & Bonelli, 2014; Bonelli et al., 2014) in the future owing to climate change. It is expected that future precipitation could change between −20% to 0% and −40% to −10% for the early (2010–2040) and late (2070–2100) time periods, respectively, with an increase in temperature of between +0.5 and 1 °C and +1.5 and 3.5 °C, respectively. These climatic scenarios translate into a reduction in water availability similar in magnitude to the change in precipitation; however, owing to an increase in temperature, it is expected that such a reduction will be more prominent during the spring and summer months as compared to winter and fall. Owing to the severity of these impacts, several projects have been developed during the last several years to promote climate change adaptation strategies. Among them, one of the most overarching has been the MAPA project, which provides the basis for the study presented herein (Ocampo-Melgar et al., 2016).

MAS has 6.5 million inhabitants and covers an area of 2274 km^2, of which 616 km^2 are developed, with a population density of 9540 inhabitants per km^2 (Banzhaf, Reyes-Paecke, Müller, & Kindler, 2013). Since the 1990s, a continuous urban sprawl has occurred, which is expected to continue over the next decades (Puertas, Henríquez, & Meza, 2014, Henriquez-Dole et al., in review). The population has increased at an annual average growth rate of 1.01% during the period of 2002–2012, and the urban area has expanded at an estimated rate of 800 ha per year (Puertas et al., 2014; Romero et al., 2012). The metropolitan area is a conglomerate of 34 municipalities, but does not constitute an administrative unit in the Chilean institutional organization. The lack of a metropolitan authority has been highlighted as a major difficulty for implementing several environmental initiatives, including climate change adaptation plans (Barton and Kopfmüller, 2016; Chuaqui & Valdivieso, 2004). MAS shows a marked spatial segregation of the population based on income level and the budgets of the municipalities depend on the resident incomes; consequently, poor people live in poor municipalities (Kabish et al., 2012; Romero et al., 2012). The quantity and quality of green spaces are correlated with municipal incomes, and consequently, the higher income municipalities have larger areas of green spaces, which are well maintained, whereas the lower income municipalities have smaller green spaces, which are less maintained (De la Barrera, Reyes-Paecke, & Banzhaf, 2016; Reyes-Paecke & Figueroa, 2010; Romero et al., 2012). Residential gardens follow the same spatial distribution pattern, with a greater size and vegetation coverage as the income of the residents increases (Reyes-Paecke & Meza, 2011). Furthermore, low-income groups are experiencing environmental inequality as they are exposed more to negative impacts of climate change such as flooding and heat, and higher levels of atmospheric pollution (Fernández and Wu, 2016; Krellenberg, Müller, Schwarz, Höfer, & Welz, 2013).

3. Methods

3.1. Irrigation of public green spaces

Three main tasks were carried out to analyse the water consumption for irrigation of public green spaces: (i) the mapping and classification of public green spaces, (ii) a water consumption analysis of green spaces using water meter recordings for the 2010–2014 period, and (iii) interviews with 24 urban park managers. Green spaces were digitized from high-resolution satellite imagery (RapidEye 5m., 14/09/2013) using a supervised land-cover classification and the resulting maps were applied using ArcGis™. Green spaces were classified according to their function in urban parks, sports areas, and spaces associated with roads (such as roundabouts and medians). For the present study, only urban parks irrigated with drinking water were considered because we could obtain water meter data. Urban parks were classified into two sizes: large (area > 10,000 m^2) and small (area > 10,000 m^2). A total of 191 large and 3,641 small parks were identified. We did not analyse the parks that use their own water sources for irrigation (81 large and 1759 small parks), because they did not have any water consumption records. Alternative water sources are water pits and channels coming from the Mapocho or Maipo River. The monthly water consumption was obtained from a database of drinking water meters provided by Aguas Andinas S.A., a private water utility serving most of the population of Santiago. Thus, the monthly water consumption during the period of 2010–2014 for 110 large parks and 1882 small parks was obtained. A sample (n = 480) was extracted for measuring the vegetation and lawn cover via very high resolution satellite images. To differentiate lawn from trees and shrubs the NDVI (Normalized difference vegetation index) was used. Finally, interviews with 24 park managers were conducted to identify the irrigation technologies used, frequency and seasonality of irrigation, and the criteria utilized for defining the irrigation

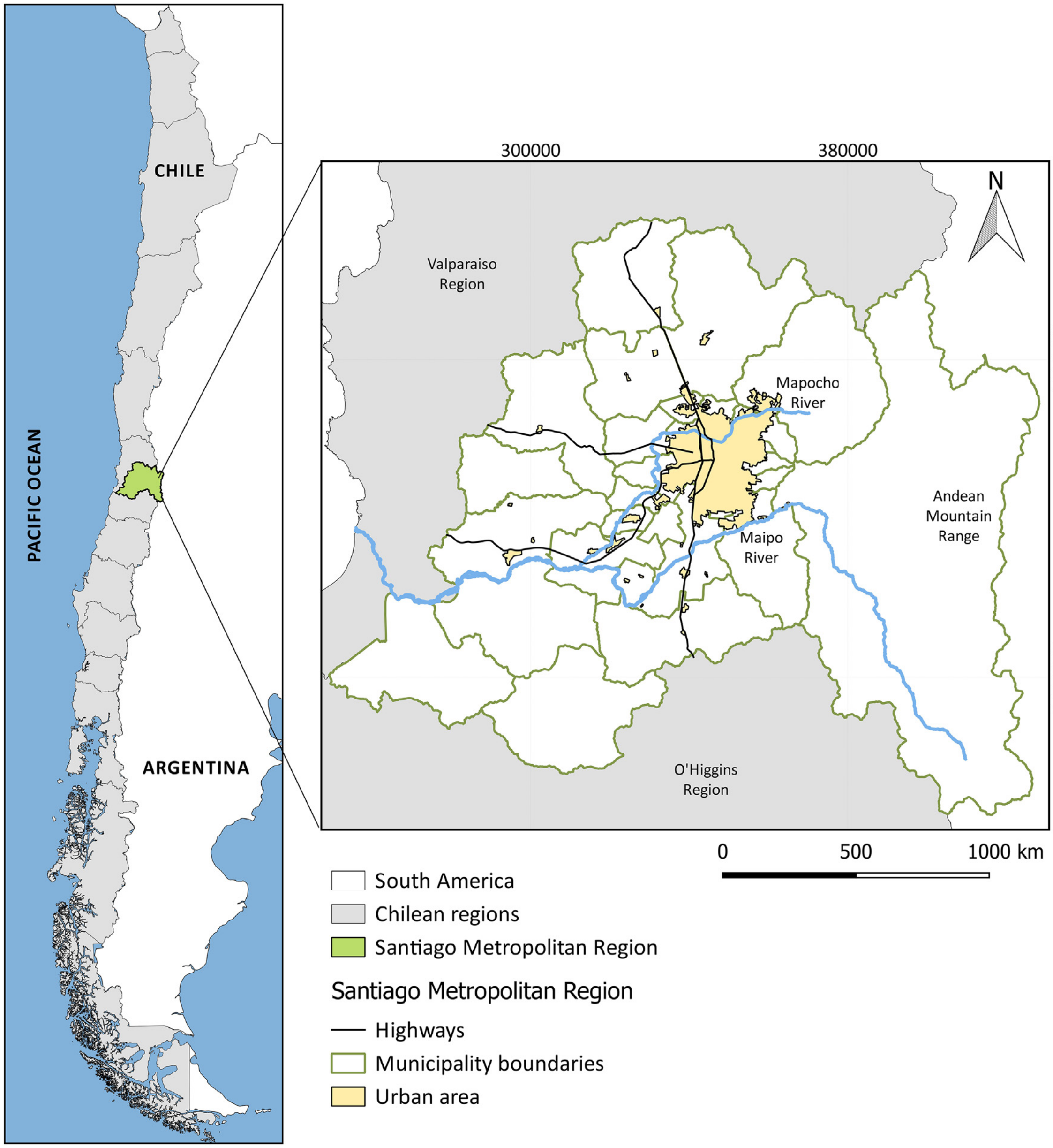

Fig. 1. Metropolitan area of Santiago (MAS) location.

needs and intensity. The qualitative and quantitative data were integrated to assess the opportunities to improve the irrigation efficiency in public green spaces when considering the social and institutional context of MAS.

3.2. Residential gardens irrigation

To determine the water consumption required to irrigate residential gardens, two main sources of information were used: a survey conducted on a representative sample of 543 residences in Santiago in 2013, and a dataset of monthly water volume consumption by residences in Santiago from 2011 to 2014, metered by the water utilities. The survey, applied through a face-to-face interview, asked about household and dwelling characteristics and behaviours, with a focus on water consumption. The survey included five groups of variables that influence water consumption: household characteristics (number of people, built surfaces, and garden size), bathroom characteristics (number of bathrooms, toilets, showers, and tubs), the presence of devices with a flow regulator or low water consumption, kitchen appliances (dishwasher or washing machine), and garden characteristics (swimming pools, ponds, sprinkler irrigation systems with or without a timer, lawn surfaces, trees, and shrubs). The sample was selected randomly through a two-stage process in which a city block was first randomly selected and five residences were then randomly selected in each block. Because the focus of the survey is water use, 172 residences, 32% of the samples, were randomly selected from a high-income stratum defined by six municipalities, where according to our consumption database, per-residence consumption is highest. Oversampling of this stratum was done to achieve a higher precision. Using the addresses of the residences in both datasets (survey and monthly water consumption), a combined set of information was created.

Because no exact information exists regarding the volume of water used for irrigation in each household, this volume was approximated based on the difference between the amount of water used each month and the amount of water used during the month with the least consumption, typically during the winter months (a similar strategy was used by Mini, Hogue, & Pincetl, 2014). The lawn area was estimated

multiplying the self-declared garden area with the associated lawn cover proportion. From the full sample 87% of the households lived in houses (instead of apartments), and only 99 of them reported information about garden size, lawn cover and household income. This estimate of the volume of water used for irrigation was decomposed for each group of houses according to income (3 groups) and lawn area, using a coefficient of water use per unit of area, as explained in the following section.

3.3. Hydrological model of green space irrigation

The Integrated Hydrological Model at the Residential Scale (IHMORS) (Herrera et al., 2017, 2018) was used in this study to simulate the irrigation needs of green spaces in Santiago. IHMORS is a continuous physically based model for simulating the hydrological processes in urban areas, with a strong focus on green infrastructure at the local scale (i.e., interception and surface retention, infiltration, percolation, evapotranspiration, surface and subsurface runoff, and redistribution). Because the model continuously simulates the dynamics of soil moisture and its driving processes, it allows modelling both the rainfall-runoff transformation and the irrigation needs to ensure a certain water content is available for the vegetation. The input data include (1) meteorological information, (2) the time step Δt of the simulation, (3) the spatial configuration of the subareas, and (4) each subarea's physical properties. Although an optional irrigation program defined by the user can be entered, the model can compute the irrigation needs so that the soil moisture θ in the top layer is never less than a certain desirable value. Fig. 2 shows all the hydrological processes that the model can simulate at each Δt. Further details regarding the mathematical representation of different processes in the model are available from Herrera et al. (2017).

As a representative implementation, IHMORS considers 1 m^2 of grass with a 1% slope, and 1.2 m of sandy loam soil, which is typical of the study area. The parameters for this type of soil correspond to the average values proposed by Rawls, Brakensiek, and Saxton (1982). Using a time step of Δt = 15 min, the model was run for year 2012, in which a total annual precipitation of 295 mm was measured (i.e., a normal annual precipitation for Santiago). Input data included hourly records of precipitation, net solar radiation, relative humidity, wind velocity, and air temperature; these hourly values were assumed to be constant within each hour. The following grass parameters were also considered (Allen, Pereira, Raes, & Smith, 1998; Zou, Caterina, Will, Stebler, & Turton, 2015): crop coefficient K_c = 0.9, leaf area index k = 2.8, and maximum interception capacity S = 0.27 mm. Finally, the field capacity of the soil, θ_{FC} = 0.207 (Rawls et al., 1982) was used as the threshold value to be reached daily to estimate the irrigation needs. Eventually, values of this parameter measured for different locations rather than a single value from the literature could be used for a more precise simulation using the model. This would allow reflecting better the local attributes of urban soils, if existent.

3.4. Comparison between observed and estimated water consumption

The last stage in the methodology compared the observed and estimated theoretical amounts of water used for irrigation of public and private green spaces. To perform such a comparison, it is necessary to first transform the observed consumption database into the comparable water consumption per unit area of vegetation, considering both the relative surface in green spaces devoted to actual vegetation and the irrigation efficiency applied in different circumstances. We then compare this value with that obtained from the physically based model. The following equations exemplify this process:

$$I_o = w_o SV, \tag{1}$$

$$I_p = \frac{w_p SV}{\eta}, \quad \text{and} \tag{2}$$

$$\beta = w_o \eta / w_p, \tag{3}$$

where I_O (m^3) is the observed irrigation water consumption for each of the parks or households, S is the total surface area of a park or house (m^2), and V is the proportion of area dedicated to vegetation (i.e., lawn grass). The observed consumption of water per area (m^3/m^2) is w_o.

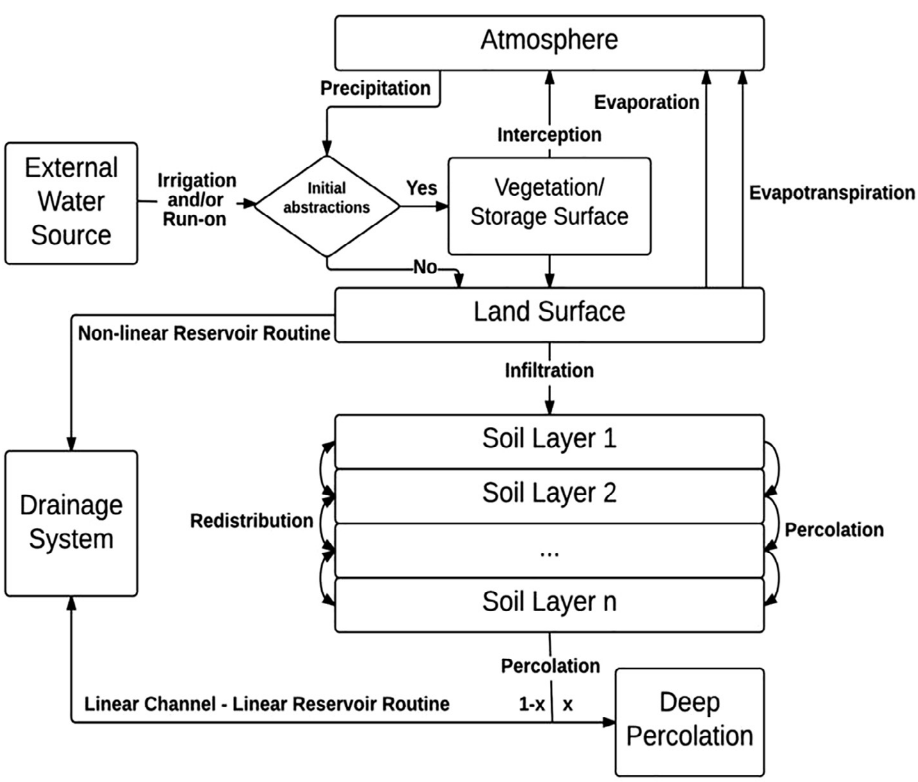

Fig. 2. Conceptual representation of the processes simulated in IHMORS at the residential scale. Water entering a subarea in the form of rainfall, run-on and/or irrigation can be intercepted and evapotranspired by vegetation or stored on the surface. The water evapotranspired from the surface becomes a surface runoff or infiltrates the different soil layers. From the last soil layer, water can achieve deep percolation, enter the drainage system, or both. *Source:* Herrera et al. (2017).

Similarly, I_P (m^3) is the inferred physical water consumption based on w_p (m^3/m^2), namely, the theoretical physically based water requirement by vegetation for the given climate and soil characteristics of Santiago calculated using IHMORS, and η is the irrigation technology efficiency related to the water actually used by plants and irrigation.

The comparison between the observed (I_o) and physically based (I_p) water consumption is represented by the adjustment factor β in Eq. (3). This last parameter includes those aspects related to the efficiency of consumption different from those associated with irrigation technology (e.g., cultural factors, people behaviour, and irrigation frequency) that will impact the final consumption. The relative values of this parameter together with the type of vegetation and irrigation technology will help us understand the possible opportunities for adaptation. The actual values for S, V, and the irrigation technology were obtained from a household survey and the questionnaires from the park managers.

4. Results

4.1. Irrigation of public green spaces

A total of 198 and 3627 large and small parks were identified in MAS, respectively (Fig. 3). Of these, 108 large parks (54.5% of all large parks) and 1880 small parks (51.9% of all small parks) had water consumption records over the five years used by the present study. Other large and small parks could also be irrigated with drinking water, but the consumption record was incomplete or non-existent. On average, large and small parks indistinctively have a vegetation cover of around 50% of their surface. The other 50% is occupied by playgrounds, trails, or paved spaces for different recreational activities. All parks have trees, shrubs, and lawn cover, and the tree cover increases proportionately with the park size. Small parks have more variable vegetation cover because trees are always present, whereas shrubs and lawn may be absent.

4.1.1. Water consumption for irrigation of green spaces

Santiago shows the characteristic annual irrigation pattern of Mediterranean regions with higher water consumption during the summer dry months. The observed seasonal variation of irrigation fits quite well with the intra-annual seasonality of the maximum and average monthly temperatures. During the cold season (May–October), the total water use for small park irrigation reaches 43,457 m^3 at a rate of 0.53 m^3/m^2 (0.088 m^3/m^2 per month), and during the warm season (November–April), these values increase up to 65,028 m^3 with an irrigation rate of 0.77 m^3/m^2 (0.128 m^3/m^2 per month). Similarly, the water use in large parks varies from 762,825 m^3 to 1,210,530 m^3 with irrigation rates of 0.29 and 0.53 m^3/m^2 during the cold and warm seasons, respectively. These data show that green spaces in MAS are irrigated throughout the year, even during the winter months.

4.1.2. Irrigation systems and frequency

The most frequently used irrigation systems are sprinkler irrigation in large parks and manual irrigation (using a hosepipe) in small parks and residential gardens. Drip irrigation has been implemented in only a small percentage of parks, and mainly in the bigger ones. The installation of more efficient irrigation systems in public spaces faces two major difficulties in MAS: first, the high installation cost that can only be afforded by the highest-income municipalities, and second, the destruction of the irrigation systems by vandalism, which affects almost all the municipalities. The larger parks use drip and sprinkler irrigation, but also have an enclosed perimeter and permanent surveillance.

During the warm season, irrigation is applied during the morning (in large and small parks) because the lowest day temperatures occur at that time, and because there are fewer users than in the afternoon. However, in most cases, the irrigation schedule is adjusted to the working hours, starting at 7:30 or 8:00 AM. Only in some of the large parks with automated systems, night irrigation has been implemented to increase the efficiency in the use of water. However, this is still an incipient practice.

Lawn cover is the most relevant factor in terms of irrigation frequency in urban parks. According the interviewees, parks with greater lawn cover are watered daily during the warm season (November–April), decreasing to two or three times a week during the cold season (May–October). Small parks with low lawn cover are watered twice a week during the summer and once a week during the winter. These data are consistent with the metered water consumption data.

Despite initiatives by various public agencies that are promoting a reduction in lawn cover to reduce water expenses, the proportion of lawn in public green spaces remains important, even in those spaces that have been built in recent years. However, there are differences in lawn cover from different municipalities, which is higher in areas with higher incomes. This correlation allows the supposition that, without a budgetary restriction, the proportion of lawn in the green spaces of lower income municipalities would also increase.

4.2. Residential consumption for irrigation

The average annual and minimum monthly water consumption for each income group of households is presented in Table 1. This table shows that, as expected, a household with higher income has higher water consumption.

Table 2 gives the sample distribution with respect to the garden size, lawn cover, and irrigation methods based on the socio-economic level. High-income households have a larger proportion of residences with larger gardens and a higher proportion of lawn cover. Regarding the garden size, 69.2% of low-income households and 58.5% of middle-income households have a garden smaller than 50 m^2. This percentage drops to 39.9% for high-income households.

A lawn is always included in the gardens of MAS, but occupying mostly less than 50% of the garden area, without relevant differences between socioeconomic groups: 92.86% of low-income households, 91.66% of medium-income households, and 82.96% of high-income households have less than 50% of their garden covered by lawn. However, the latter have the largest gardens, and thus a decrease in this percentage does not imply a similar decrease in the absolute lawn surface area.

Less than 10% of low- and middle-income households have more than 50% of garden area covered by lawn (7.14% and 8.34% respectively), but this percentage increases to 17.1% in high-income households. As in urban parks, the lawn cover influences the frequency and intensity of irrigation, and thus these figures are relevant for residential water consumption.

Most residences irrigate manually, and very few use automated irrigation systems, most in high-income households.

Using monthly water consumption data for 99 houses during the period 2011 to 2014, the average annual water consumption for irrigation and annual water consumption for irrigation per unit of lawn area, for each income group of households was calculate, (see Table 3). The average garden size in the sample is 75.6 m^2. High income households, on average, have gardens two times larger than low income households, 89.9 m^2 compared to 42 m^2. Lawn cover as a proportion of the garden is higher in high income households (31%) than in medium and lower income ones, 23% and 22%, respectively. As expected, a household with higher income has higher total water consumption for irrigation compared to medium and low-income households. But, per unit of lawn high-income households have a lower consumption of irrigation water than medium and low-income households.

4.3. Comparison of observed and theoretical irrigation rates

To estimate the water requirement of vegetation, 1 m^2 of grass with a 1% slope and 1.2 m sandy loam depth (soil characteristics of MAS)

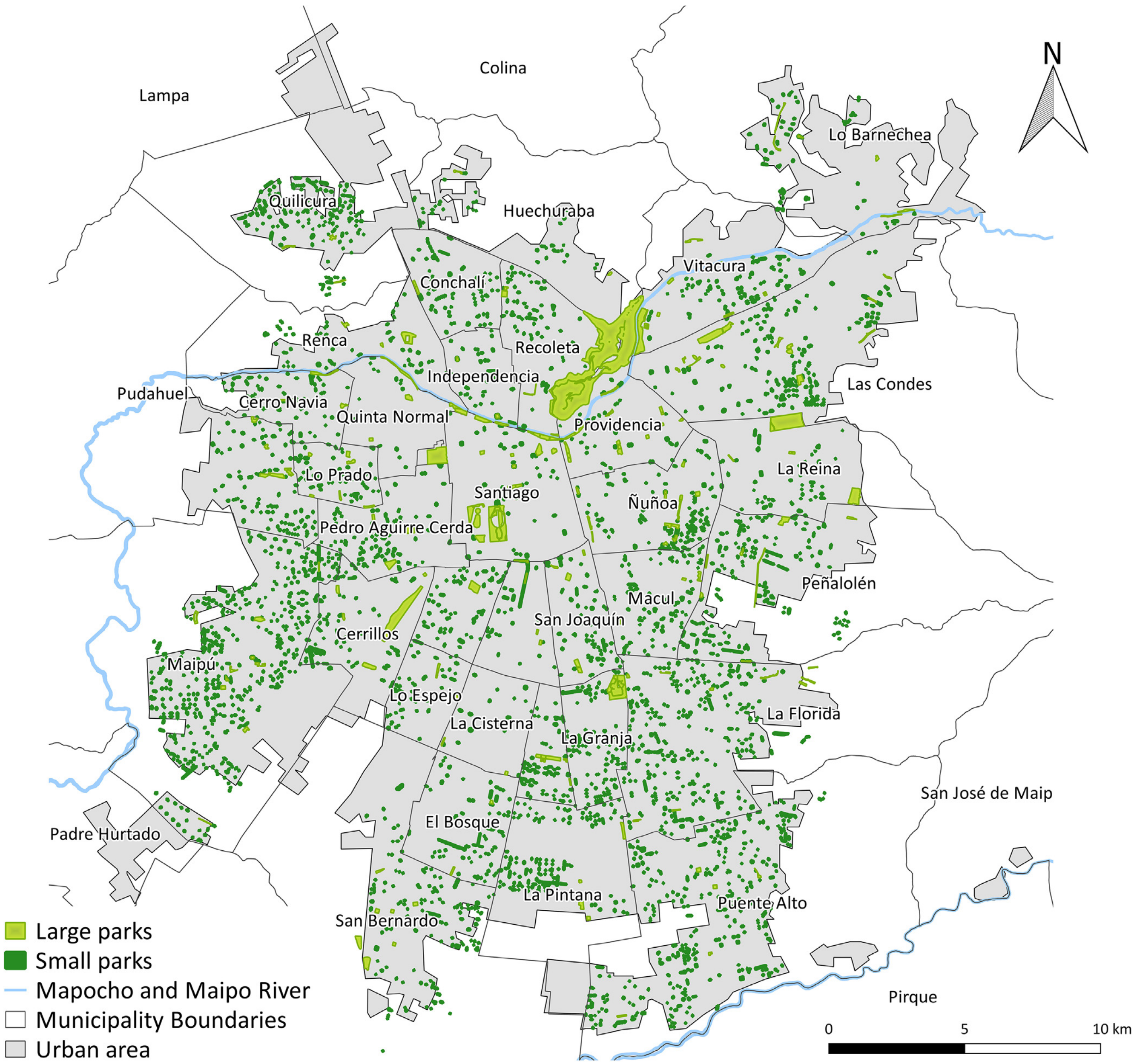

Fig. 3. Spatial distribution of large and small urban parks analysed in MAS.

Table 1
Water consumption by group, current situation (2015).

	Lowest monthly consumption (m^3/month)	Total annual consumption (m^3/year)
Low household income	20.34	290.4
Medium household income	22.96	324.1
High household income	24.54	344.4

was modelled using IHMORS. The irrigation requirements were estimated, including the amount of water needed for the soil moisture of the garden to equal its field capacity. In this way, IHMORS calculates the difference between the estimated soil moisture and the field capacity every 15 min during a one-year period. As a result, the theoretical water requirement for a typical year in Santiago (considering 295 mm of precipitation) is 0.366 m^3/m^2. During the cold season (May–October) the requirement reaches 0.023 m^3/m^2 and during the warm season (November–April) it increases to 0.313 m^3/m^2.

A comparison between the estimated and theoretical values for both public and residential gardens is conducted through a β adjustment representing different aspects related to water consumption efficiency, such as cultural norms, irrigation behaviours, and irrigation frequency, which differ from technical irrigation mechanisms, shown in Eq. (3). Manual irrigation, the efficiency of which is η = 40%, is assumed for public and private areas. The value of w_p is obtained from the IHMORS model as mentioned in the previous subsection. To calculate the value of w_o, the recollected data for public green spaces is classified between large and small parks. For both, the value of w_o is obtained as the average annual irrigation of lawn areas between 2010 and 2014. On the other hand, w_o for private cases is obtained according to the income level (low, medium, or high) for all homes with a lawn area.

Figs. 4 and 5 show the results obtained for public and private cases, respectively. In both figures, a box plot of the β values is shown. In this plot, the maximum and minimum values, corresponding to the limits of

Table 2
Sample distribution according to garden size, lawn cover, and irrigation methods based on socio-economic level.

Garden size, lawn cover, and irrigation methods		Socio-economic level		
		Low-income %	Medium-income %	High-income %
Garden surface (m^2)	Up to 10 m^2	21.8	13.85	9.49
	10–25 m^2	30.08	23.08	13.29
	26–50 m^2	17.29	21.54	17.09
	51–100 m^2	4.51	6.15	12.03
	101–200 m^2	4.51	3.08	4.43
	201–900 m^2	0	2.31	6.96
	No response	17.29	21.54	22.78
	Doesn't know	4.51	8.46	13.92
Lawn cover (% of garden surface)	91–100%	0	0	3.41
	76–90%	0	4.17	3.41
	51–75%	7.14	4.17	10.23
	26–50%	21.43	14.58	25
	10 y 25%	57.14	58.33	35.23
	< 10%	14.29	18.75	22.73
	No lawn cover			
Uses manual irrigation	Yes	98.5	99.22	95.54
Uses sprinkler irrigation	Yes	0.77	1.59	6.04
Uses sprinkler irrigation with timer	Yes	0.77	2.38	8.78

the solid line, and 50% of all values (between the second and fourth percentile) are shown. In addition, the average and median values for each case are plotted.

As expected, the median values in both figures are more representative than the average. The comparison of these values indicates that irrigation in urban parks is more efficient than in private gardens because, in the first case, β is minor and approaches 1. In fact, the median values are 1.24 for large parks, 1.78 for small parks, and 1.55 for both. In contrast, for private gardens, the median values are 12.34, 19.85, and 13.95 for low-, middle-, and high-income households, respectively.

5. Discussion and conclusions

5.1. Irrigation in residential gardens and green spaces

This article analysed the water consumption for the irrigation of green spaces and residential gardens in a Mediterranean metropolis. The first important finding is that the current water use for irrigation is higher than the modelled demand, which entails a significant chance to save water. This is a valuable antecedent for implementing climate change adaptation plans because all climate change scenarios project a precipitation decline along the next decades in the Metropolitan Area of Santiago.

An unexpected finding is the large difference between the irrigation rate of public and private spaces, the former being much more water efficient. There are two possible explanations regarding this difference: First, it could be a scale effect on the irrigation that favours the more

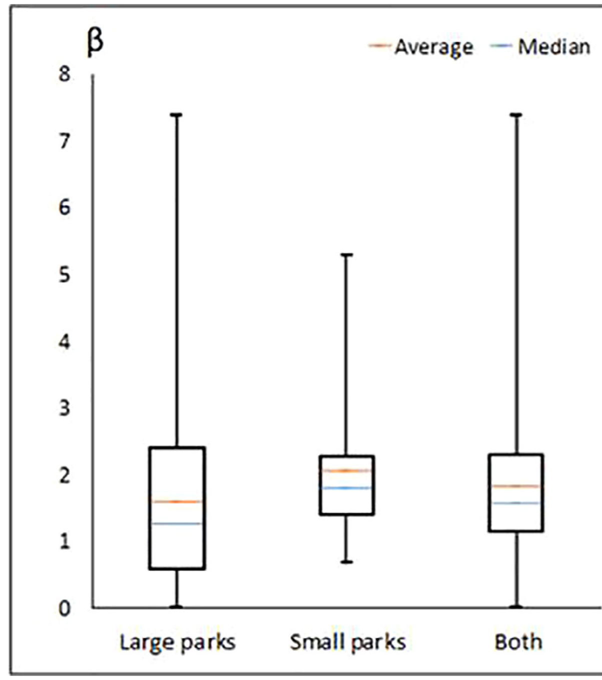

Fig. 4. Box plot for adjustment β factor for small and large parks.

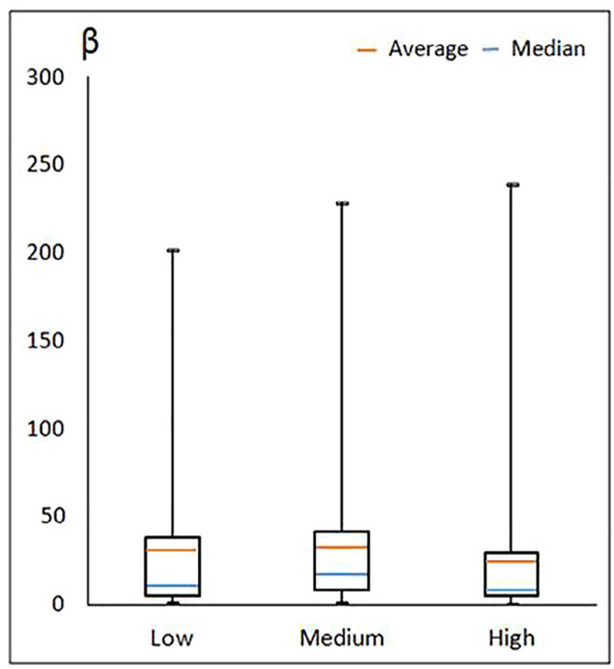

Fig. 5. Box plot for adjustment β factor for residential gardens according to household income level.

Table 3
Garden characteristics and average water consumption for irrigation by income group, 2011–2014.

Household income level	Number of Households	Garden Size (m^2)	Lawn Cover (% of garden area)	Water consumption (m^3/year)	Water consumption per lawn area (m^3/m^2)
Low-income	10	42.0	22%	72.0	31.4
Medium-income	34	62.4	23%	91.3	32.7
High-income	55	89.9	31%	115.8	25.0
All	99	75.6	28%	102.9	28.3

extensive green spaces. In this case, the difference would not be associated with the conditions of public or private property, but with the size of the green space. Our results support this hypothesis because the larger the size of a green space, the smaller the irrigation rate (m^3/m^2). Thus, small parks tend to use more water per area than large parks, and residential gardens use more water than small parks. Some physical factors may explain this scale effect; for example, in a larger green space, the soil is less compacted, and has higher humidity retention capacity, while the greater forest canopy attenuates the effect of an urban heat island by reducing the water losses through evapo-transpiration (Litvak, Bijoor, & Pataki, 2014; Shashua-Bar, Pearlmutter, & Erell, 2009). For example, Litvak et al. (2014), who conducted a study in Los Angeles, demonstrated that tree shade significantly reduces the evapotranspiration of turf grass (ranging from 0.9 to 3.9 mm/d^{-1}) allowing for a reduction in irrigation water required. In addition, according to a review by Bowler, Buyung-Ali, Knight, and Pullin (2010), shading and evaporative cooling have played a significant role in lowering urban temperatures.

A second hypothesis refers to the economic reasons. Because this study analyses irrigation using drinking water, which can be quite expensive, particularly during the summer, we assume that municipalities will be looking to reduce spending more actively than homeowners. This could be due to the existence of economies of scale in monitoring and control of consumption. For example, the time devoted by someone to this activity at a Municipality could yield larger saving than the same time spent at home. Also, different opportunity costs of their time could be part of the explanation. Municipalities manage a high number of green spaces, and hence water saving can reach a significant absolute value as well as a high opportunity value, which would be a greater incentive to increase the efficiency. In short, the greater the irrigated area is, the greater the water saving incentive. Actually, most low-income municipalities in MAS have implemented water-saving measures, which include reducing the proportion of lawn in green spaces, selecting plant species with lower water requirements, and shifting toward more xeric landscaping (Reyes-Paecke, 2014).

Over-irrigation in residential gardens has been found in other cities with a Mediterranean climate. In Zaragoza, Spain, a three-year study detected an over-irrigation in 60% of households (Salvador, Bautista-Capetillo, & Playán, 2011), whereas in the Metropolitan Area of Barcelona, this percentage reaches 45% (Domene, Saurí, & Parés, 2005). These studies have applied a similar method to evaluate the adequacy of the irrigation rates by comparing the actual consumption of a household sample with the estimated demand of the garden vegetation. Excessive watering may be related to the presence of lawns and ornamentals with high water requirements (Hof & Wolf, 2014; Salvador et al., 2011). For MAS, a previous study showed that residential gardens have a greater structural diversity than public green spaces, that is, they contain lawns, shrubs of different sizes, and trees (Reyes-Paecke & Meza, 2011), which may require a higher irrigation rate. It may also result in the maintenance standard of a residential garden far exceeding that of public spaces, and the owners applying excessive watering to avoid the appearance of slightest water stress symptom in the vegetation, as was detected in Zaragoza by interviews to gardeners and owners (Salvador et al., 2011). A research on the criteria of plant species selection for public green spaces applied by AMS Municipalities stated that the two main criteria used are the low water requirement and the resistance to drought, and that it has also contributed to increase the native species presence in green spaces (Reyes-Paecke, 2014). Therefore public spaces are more likely to have climate-adapted species than residential gardens.

Regarding private gardens, a positive correlation between the monthly irrigation amount and family income level was found. This is due to the higher-income groups having larger gardens and a higher proportion of turf grass than lower-income groups (Reyes-Paecke & Meza, 2011). The same correlation between irrigation volume and income level was found in Barcelona, Phoenix, and Los Angeles (Domene et al., 2005; Jenerette, Harlan, Stefanov, & Martin, 2011; Mini et al., 2014; Parés-Franzi, Saurí-Pujol, & Domene, 2006). In all cases, the landscaping based on extensive lawn surfaces seems to be the main driver of over-irrigation. Like in other Latin American cities, green spaces tend to be larger and better maintained in the higher income districts (Parra, Gomez, Fleischer, & Pinzon, 2010; Wright-Wendel, Zarger, & Mihelcic, 2012).

Complementing the above explanations, it is important to mention that the methods used have certain limitations and uncertainties. For example, unlike the case of parks, we do not have a direct measurement for the irrigation water use of residential gardens. Similarly, the lawn surface was reported based on a survey by households, but was directly observed in the case of parks. In the calculation of the theoretical consumption of water for irrigation we didn't take into account the variability of some factors within the city such as elevation, soil and climate. All these methodological approximations can potentially imply an overestimation of residential irrigation water use. Future work could address these issues by using metering devices or a mixed methods approach (Willis, Stewart, Panuwatwanich, Williams, & Hollingsworth, 2011) that can help get a better measurement of irrigation flows, and remote sensing techniques to estimate actual garden and lawns surface.

5.2. Climate change and irrigation in semiarid and Mediterranean cities

Increasing the vegetation cover has been proposed as a strategy to cope with increased temperatures triggered by climate change, and to mitigate the negative impacts on human health (Bowler et al., 2010). But this strategy needs to be carefully evaluated according each location characteristics as in the Mediterranean and semi-arid cities, where there is a trade-off between increasing vegetation and water use, which is a scarce resource. However a well-designed mix of shading trees, shrubs and flowers help to improve soil water retention. Because of their more extensive root system than of the lawn, trees and shrubs are capable to use a larger volume of soil moisture, and as such do not deplete soil water (Hilaire et al., 2008). Also it has been demonstrated that woody plants do not need regular water application to maintain an adequate water uptake and plant health, reducing the irrigation needs (Lowry, Ramsey, & Kjelgren, 2011). For these reasons Lowry et al. (2011) recommend to increase the tree cover in semiarid urban landscapes to reduce water use for irrigation. Complementarily, most cities have public policies oriented to increase the amount of green spaces, particularly in deprived neighbourhoods. Therefore changes in urban landscaping are increasingly important for both to improve life quality and to cope with climate change.

The evidence of over-irrigation provided in this work allows the assertion that it is possible to increase the vegetation cover without increasing the water consumption, if the current irrigation practices are modified for improved efficiency. In contrast, the data show that green spaces (both residential and not residential) in a Mediterranean and semi-arid city such as MAS are irrigated throughout the year, even during the winter months. Hence, in a drier and warmer climate, a future watering scenario could become a major cost, as well as a restriction for green space permanence.

The results also show that there are significant possibilities for climate change adaptation. Although annual rainfall has declined and will continue to decline over the next few decades (Boisier et al., 2016; Meza et al., 2014), MAS can conserve and even increase its total vegetation cover by modifications in the existing irrigation practices and in urban landscaping. The water saving potential in both green spaces and residential gardens is relevant. However, the analysis shows that the saving is much greater in residential gardens, which is consistent with previous studies published thus far, showing over-irrigation as a widespread practice. This is correlated with the global expansion of a garden model based on extensive lawns and ornamental plants with high water requirements, which are commonly irrigated with sprinklers. Several authors have suggested that the garden size is less

significant for explaining outdoor water consumption than the garden design (Hilaire et al., 2008; Hof & Wolf, 2014). Our data suggest those higher income households are more efficient, implying potential increases in efficiency in lower income households.

In addition to improving the green space designs and an overall adoption of the so called water sensitive urban design (Coutts, Tapper, Beringer, Loughnan, & Demuzere, 2013), shifting to drought-tolerant species is also required for reducing water consumption. Overall, in arid and semi-arid cities this reduction is possible by adopting strategies focused on water-soil-plant interactions, such as those proposed in the water-sensitive cities model. Another strategy to accomplish this reduction is that of alternative irrigation systems. In this case, the focus must be on alternative sources coming from rainwater harvesting (Aladenola and Adeboye, 2010; Chanan and Woods, 2006; Che-Ani, Shaari, Sairi, Zain, & Tahir, 2009) and water reuse and recycling, particularly of gray water, which correspond to 60–75% of the total residential wastewater, and have relatively low levels of organic matter and nutrients (Eriksson, Auffarth, Henze, & Ledin, 2002). Thus, gray water is a good source for irrigation purposes once the pollutants have been removed through a combination of physical removal processes and some chemical or biological treatment (Li, Wichmann, & Otterpohl, 2009). Nevertheless, the increase in irrigation efficiency requires more than a technical solution because it is subordinate to the solution of social problems such as vandalism. Therefore, in MAS, and particularly in more deprived neighbourhoods, technologies improving irrigation must be accompanied by campaigns and working programs with local communities. Additional adaptation strategies at the household level should consider reviewing the tariff schedules, existing subsidies, and support for addressing leaks, arid garden design and irrigations systems improvements.

Public green spaces and residential gardens are key elements in adapting cities to climate change by contributing toward the mitigation of their negative impacts on human health and. However, further research is strongly required to study the trade-offs between these benefits and the costs of irrigation in semi-arid and Mediterranean cities. Also further research should cover the complexities around implementing voluntary steps towards climate change adaptation in urban green spaces irrigation.

Acknowledgements

We would like to thank Aguas Andinas SA for supplying the water consumption data, as well as Parque Metropolitano for facilitating the conduct of interviews and to provide valuable information for this study. We also thank Francisco Aguayo for the preparation of the maps. This research was supported by IDRC (Project 107081-001), and CONICYT (CONICYT/FONDAP 15110020).

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